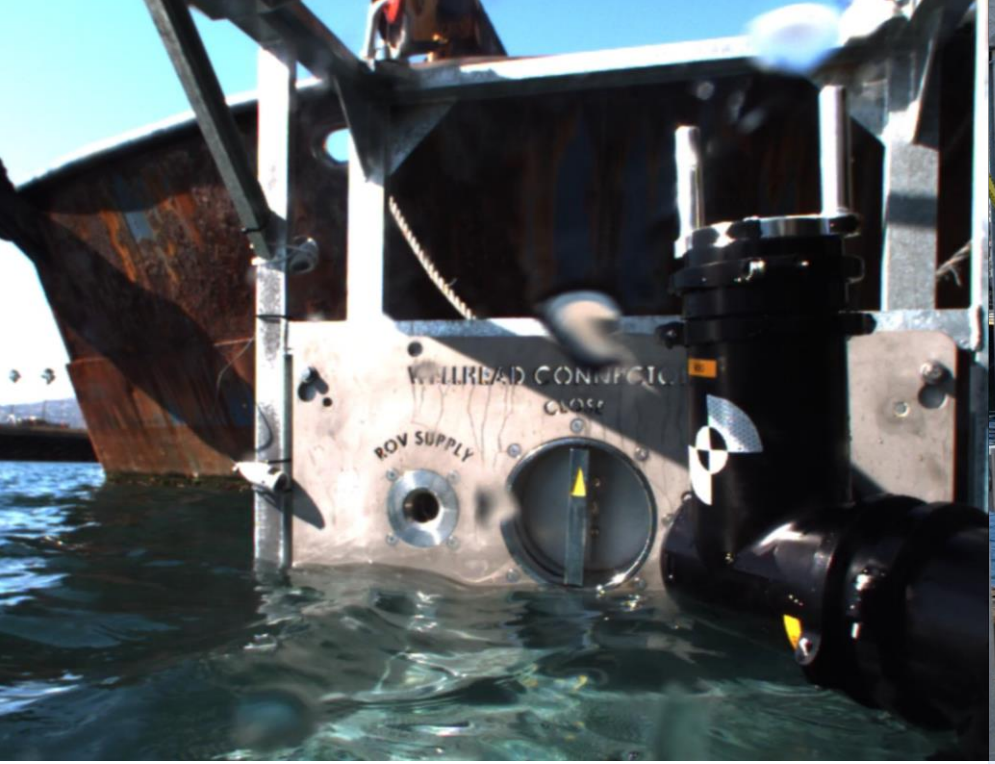

Development of a Robotic Limb for Underwater Mobile Manipulation

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R. Detry, D. Levine, M. Gildner

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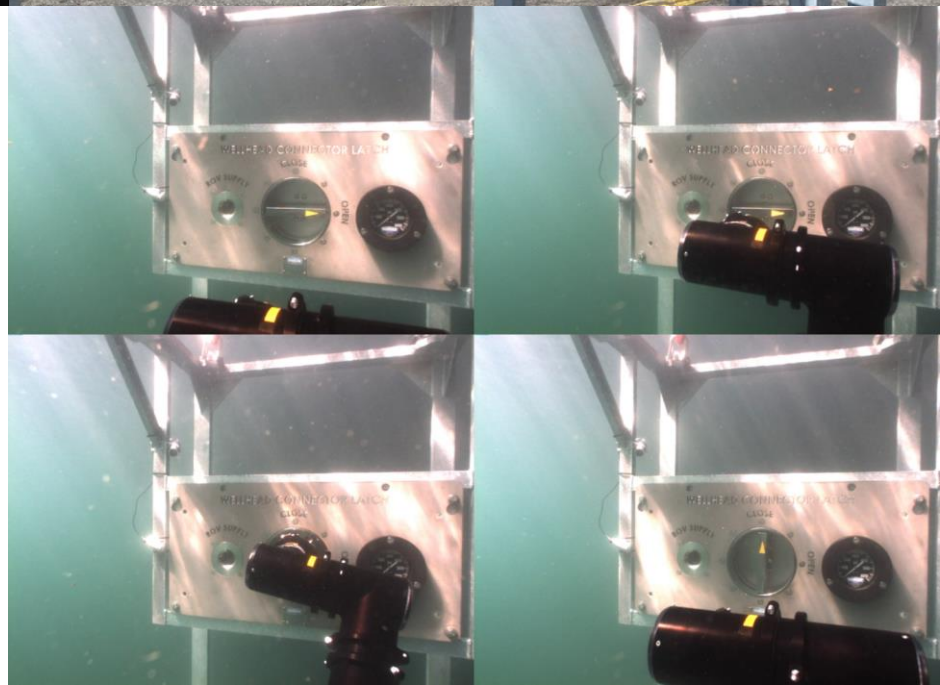
Jet Propulsion Laboratory
California Institute of Technology



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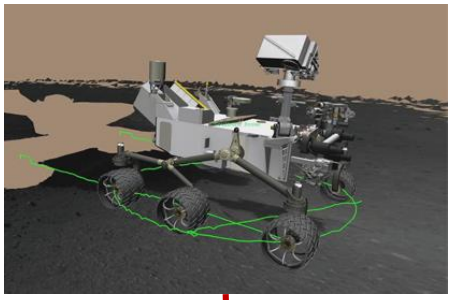
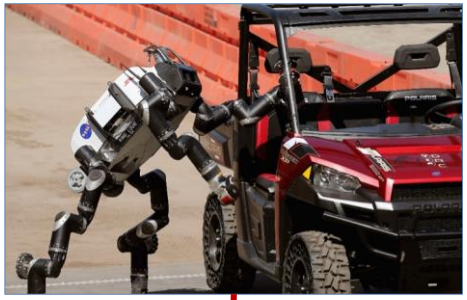
Motivation

Develop manipulation technologies to *extend* the effectiveness, functionality and accessibility of ROV Operations by adapting technologies from Mars Rovers and other JPL robotic manipulation systems.





Live 3D Scene Reconstruction of Robot Workspaces

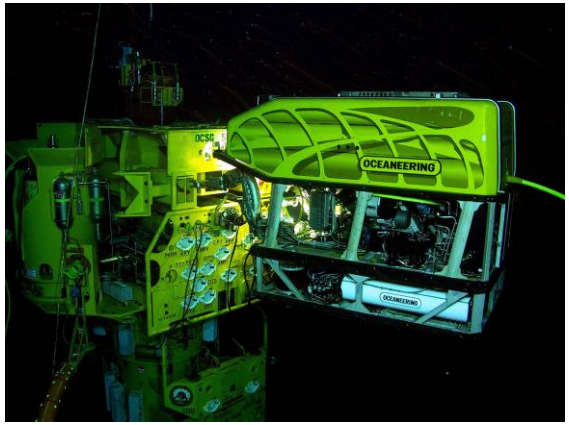
- Increased operator situational awareness
- Vision in the loop operations

Supervised Autonomy for Intent-Based Operations

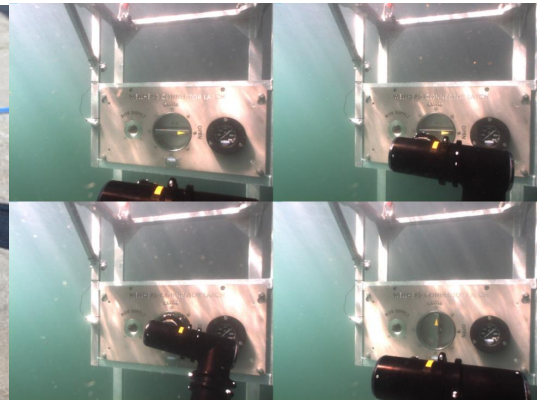
- Point → Click → Simulate → Execute Workflows

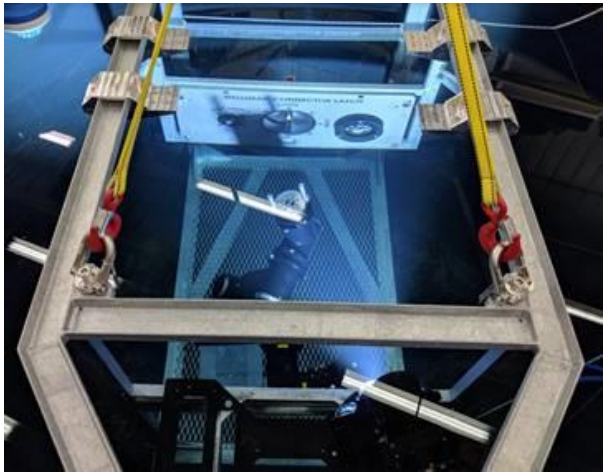
Dexterous Limb Hardware Architectures

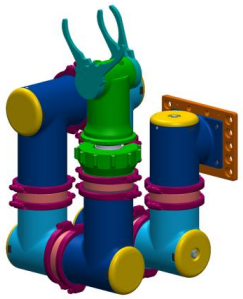
- Low integration required on host vehicle
- Deploy on wider range of vehicle classes
- Mobility as manipulation

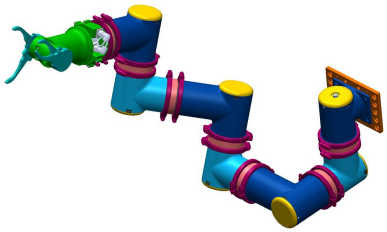


AquaSimian Limb







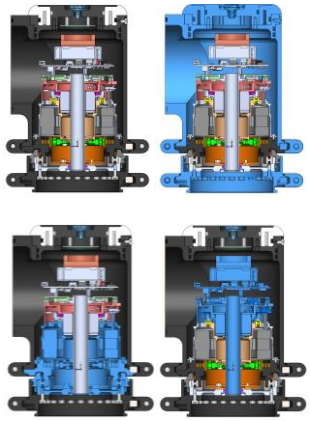


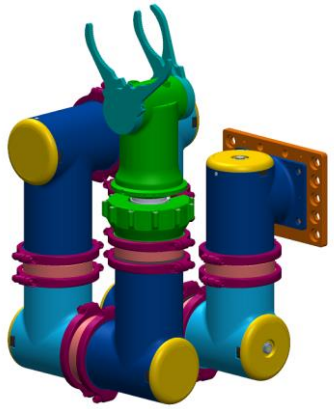
Specifications	
Reach:	1.25m
Lift at Full Extension:	20kg
Max Speed at Gripper:	2 m/s
Functions:	10
Control:	FWD Kinematic Position Ctrl 6-Axis Force/Torque Ctrl
Limb Power:	100V / 50A
Telemetry:	EtherCAT / RS-485
Weight in air:	40kg
Weight in water:	15kg

Outline

Hardware Design

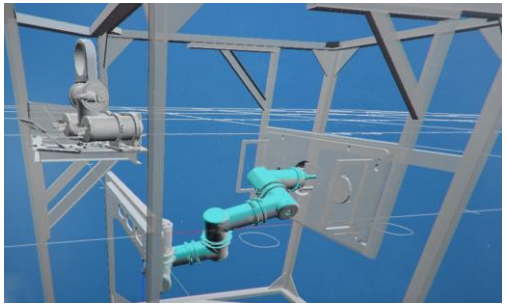
Actuator, Limb Architecture

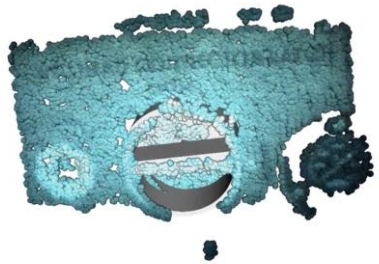




Concept of Operations

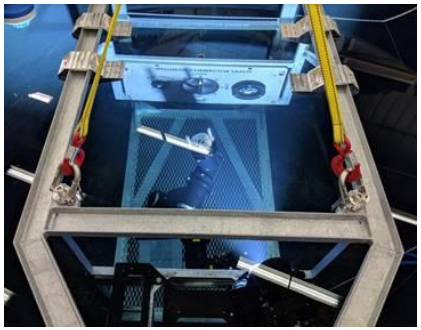
Operator Interface, Automation, Behaviors

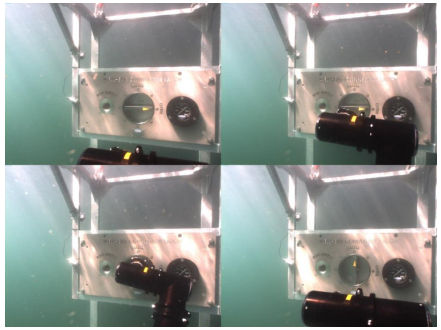




System Testing

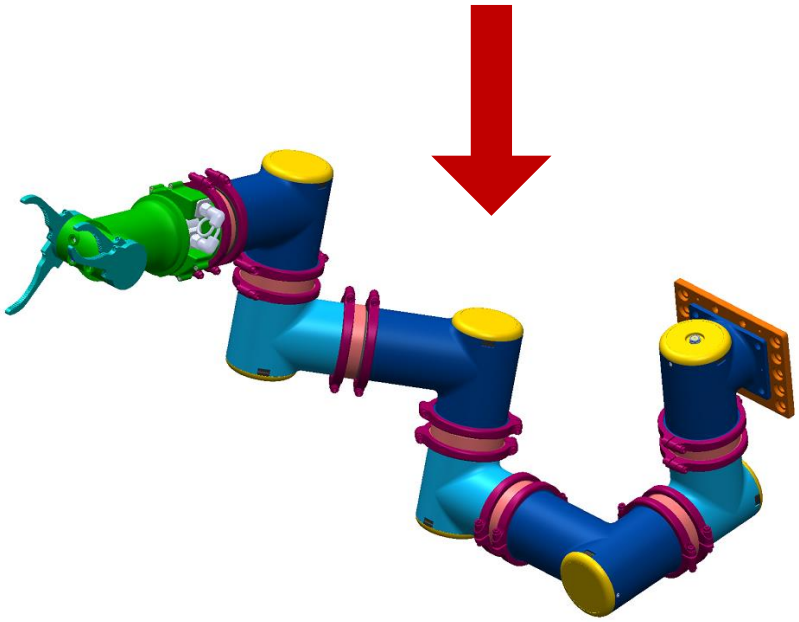
Laboratory, Field





Hardware Design Objectives

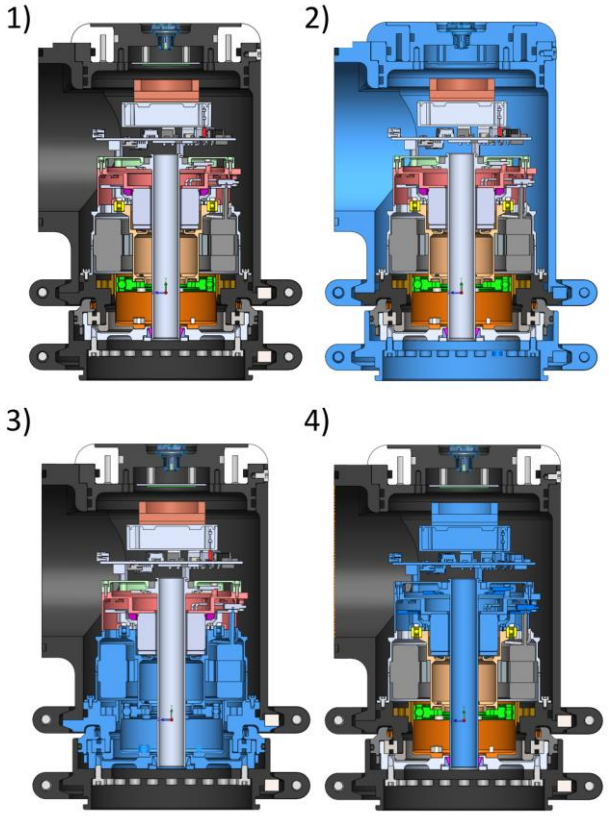
- Generalized, Modular, All-Electric Design
- 7 Degrees of Freedom
- Absolute Joint Position Sensing
- 3 Degree of Freedom End Effector with F/T Sensing
- Human–Scale Reach and Force Application
- 360°+ Joint Rotation
- Compartmental, Vacuum Sealing at 30m Depth
- Leverage Heritage of Robosimian System



S-PRIME Actuator

Sealed - Performance Robotic Integrated Modular Electric

- Developed around 100V Brusheless DC Frameless Motor
- 160:1 Harmonic Geartrain with Cross-Roller Bearing on Output
- Embedded Elmo Gold Whistle Ethercat Motor Controller
- Custom Actuator Motherboard PCB
  - Brake Driving
  - Position Sensor Comms
  - Pressure, Temperature, Humidity Sensing
  - Actuator Serial Bus Comms
- Magnetic Brake
- Teflon Rotary Dynamic Seal and O-ring static seals



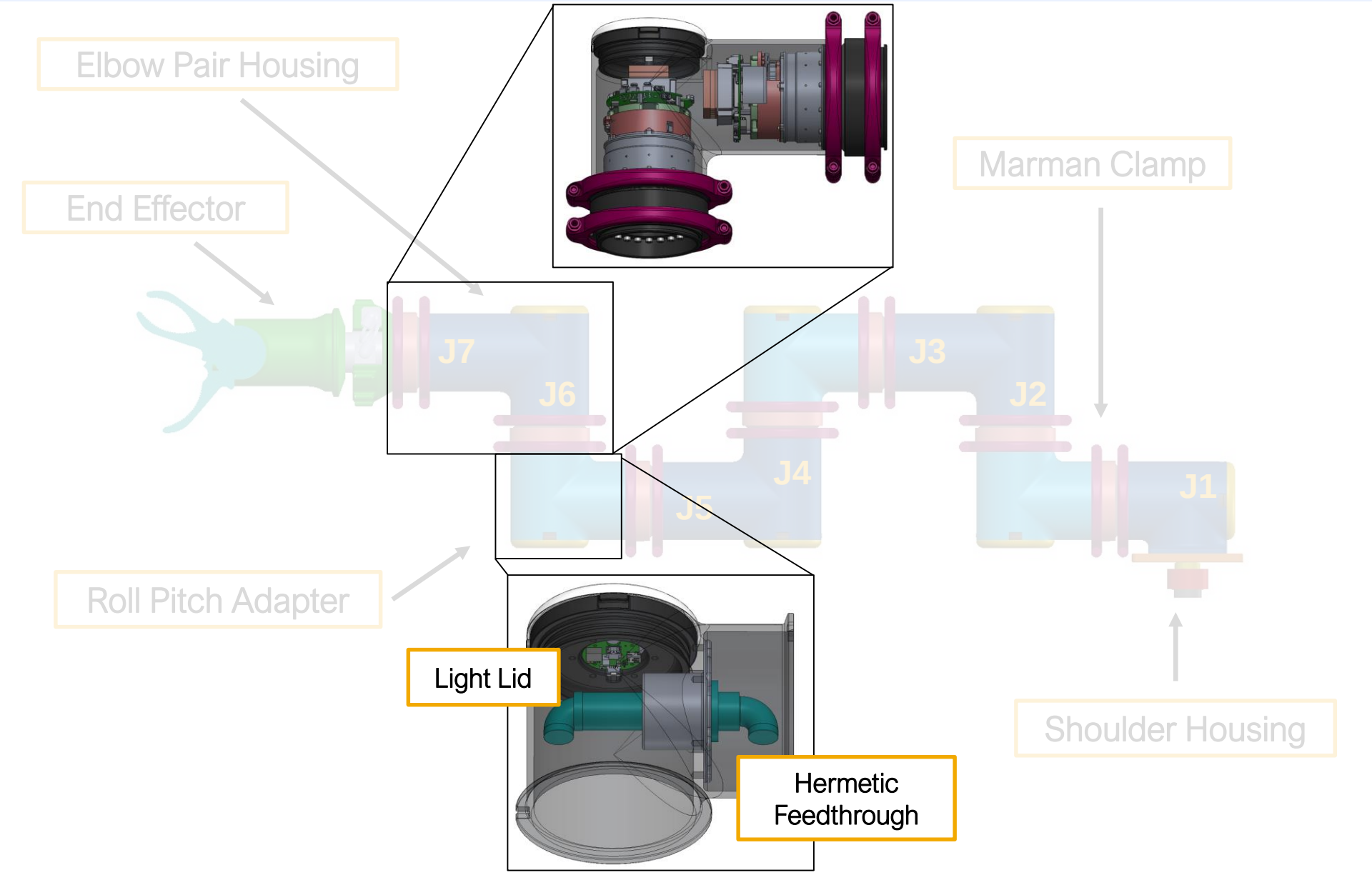
1) S-Prime Actuator 2) Housing
3) Drivetrain 4) Electronics

S-PRIME Actuator: Spec Sheet

Sealed - Performance Robotic Integrated Modular Electric

Parameter	Value
Size	225 mm (L) x 120 mm (Dia)
Depth Rating	30m
Weight (air)	4.2 kg
Weight (water)	1.6 Kg
Max Torque	285 Nm
Max Speed	135 deg/s
Braking	220 Nm
Power	100V, 14A
Communication	Ethercat, RS-485

AquaSimian Limb: Architecture



AquaSimian Limb: Environment Monitoring

Purpose

- Monitor internal housing state to detect for leaks
- Enable auto e-stop in case of leak

Sensors

- Pressure, temp, humidity

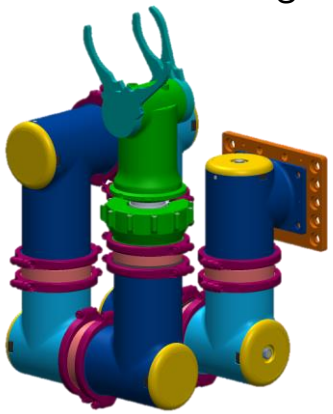
Process

- Vacuum and dry purge each sealed volume through valve on housing lids
- Query actuator motherboards sensors over serial bus
- Provide visual display of sensor readings compared to thresholds
- Trigger auto-estop if loss of telemetry

AquaSimian Limb: Serviceability

Stow

- Compact stow configuration for transport and vehicle integration



2ft X 2ft X2ft

Actuator Servicing

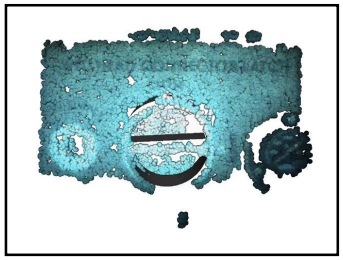
- 2-Bolt Marman Clamp interface for actuator removal
- Lid for actuator electronics access

Light Lid

- Lid embedded with LED Array and Controller
- Actuator State
- Leak Diagnostics

Concept of Operations

Vehicle Approach Task Panel → Manual Anchor to Task Panel → Enable Live Workspace Reconstruction

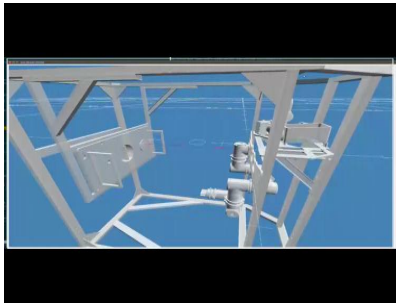


Point Cloud

Obstacle Map

Interface CAD Library

Operator Workspace



Select Target Area → Interface Identified → Select Desired Operation → Request Plan → Motion Plan Generated → Review Simulation → Execute Plan

Review Simulation → Request Plan

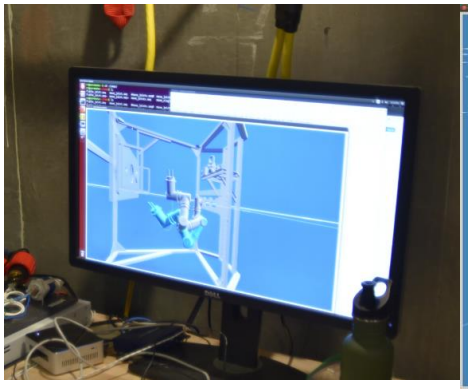
Concept of Operations: Control

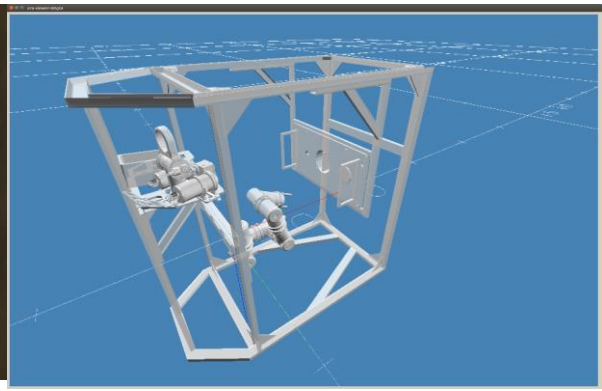
Operator Computer (Intel NUC)

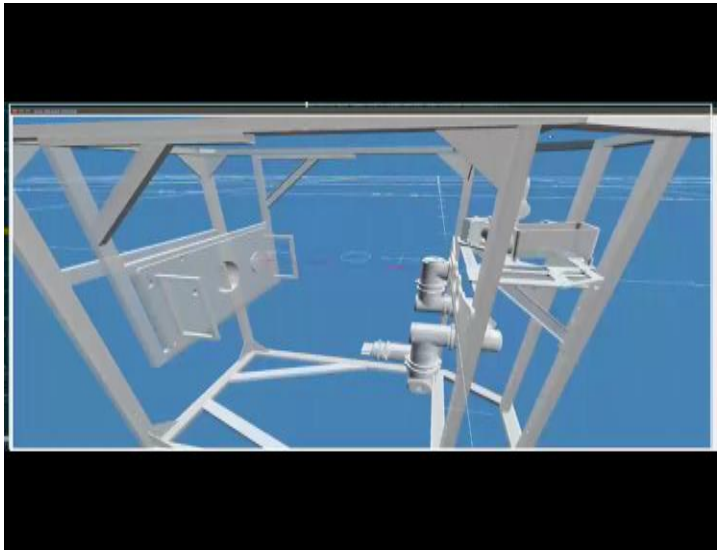
- Operator Control Interface
  - State Visualization
  - Behavior Selection
  - Move Preview
- Module Control
  - Start/stop of control modules
  - Software EStop

Limb Computer (Intel NUC)

- Trajectory Generator
- Motor Control Interface
- Environmental Monitoring

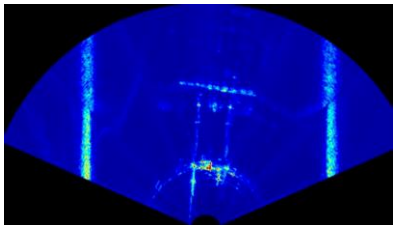


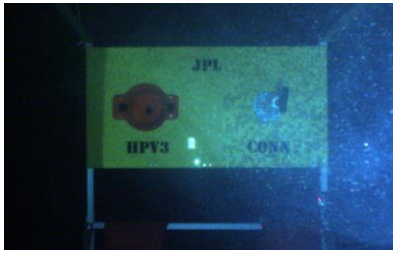




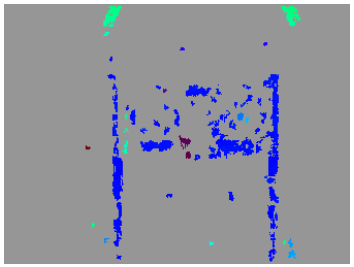
Concept of Operations: Perception

Sensor Head

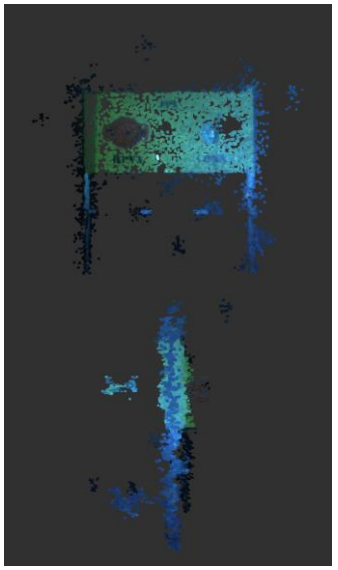




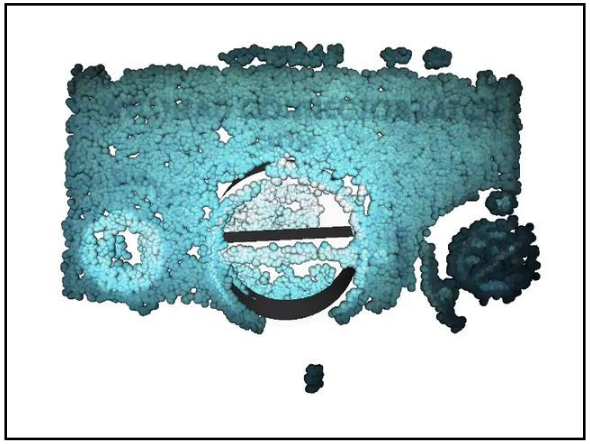
Raw Images



Raw Pointclouds



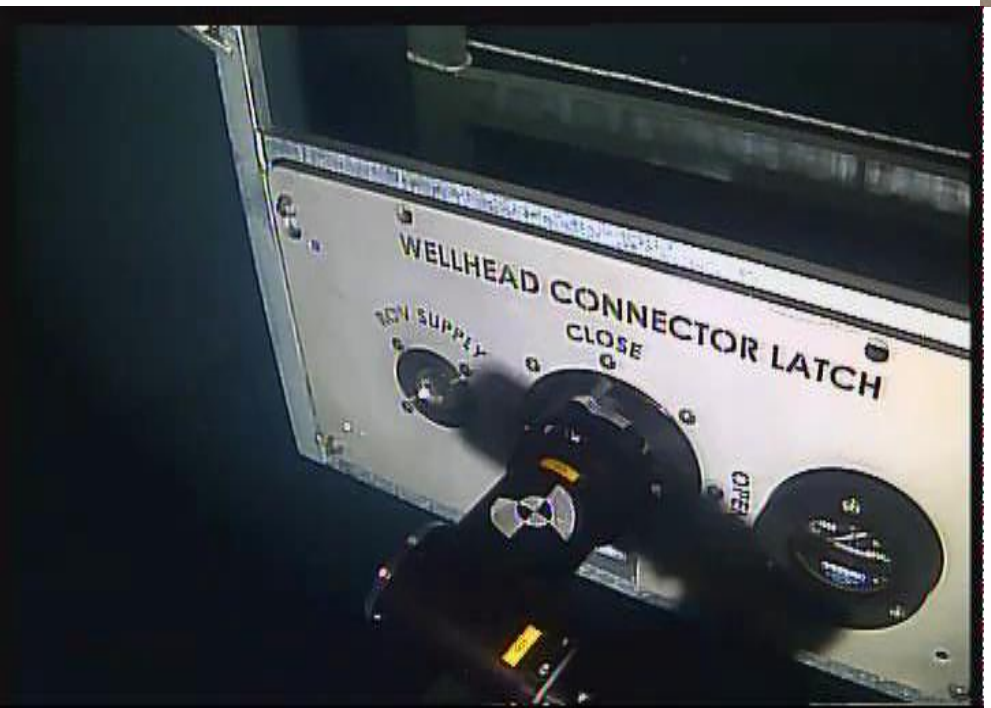
Fused Pointcloud



CAD Fit

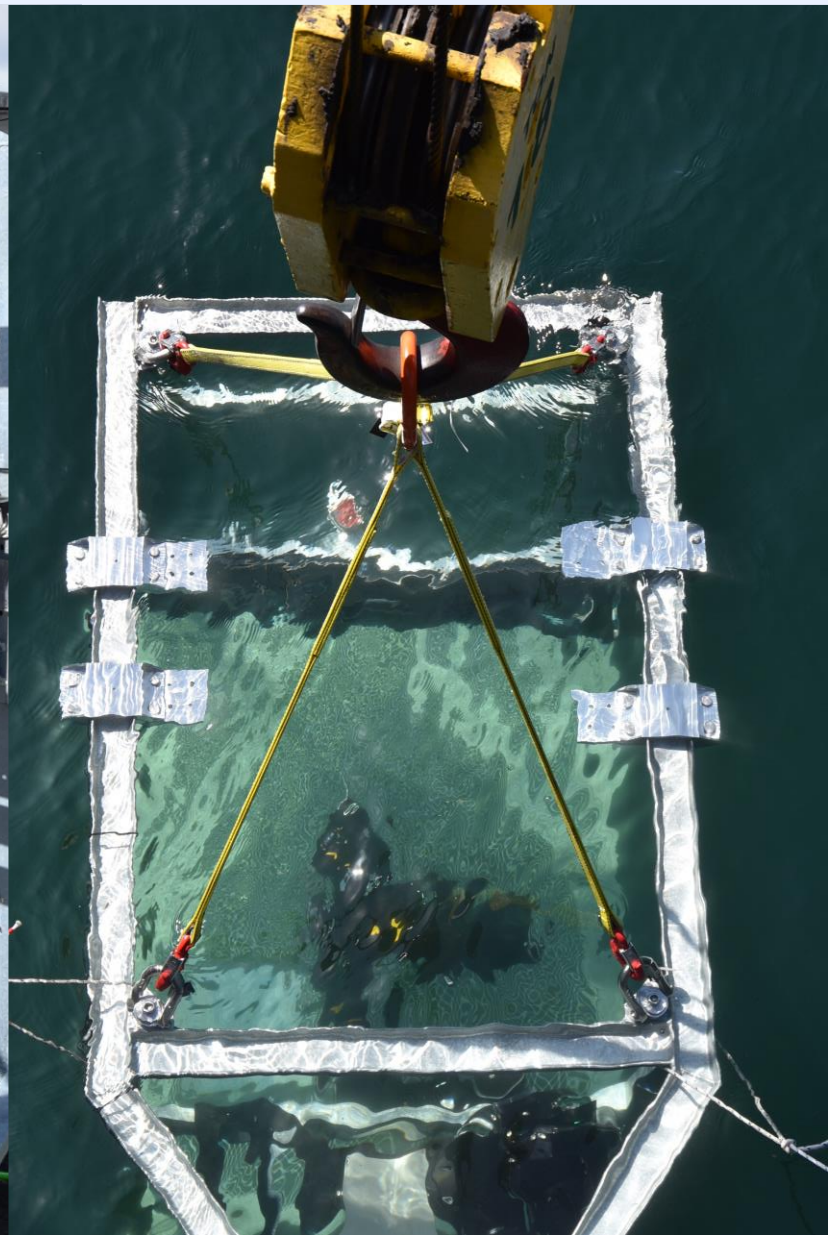
System Testing: Lab

Limb Moving Through Hand-Eye Calibration Postures

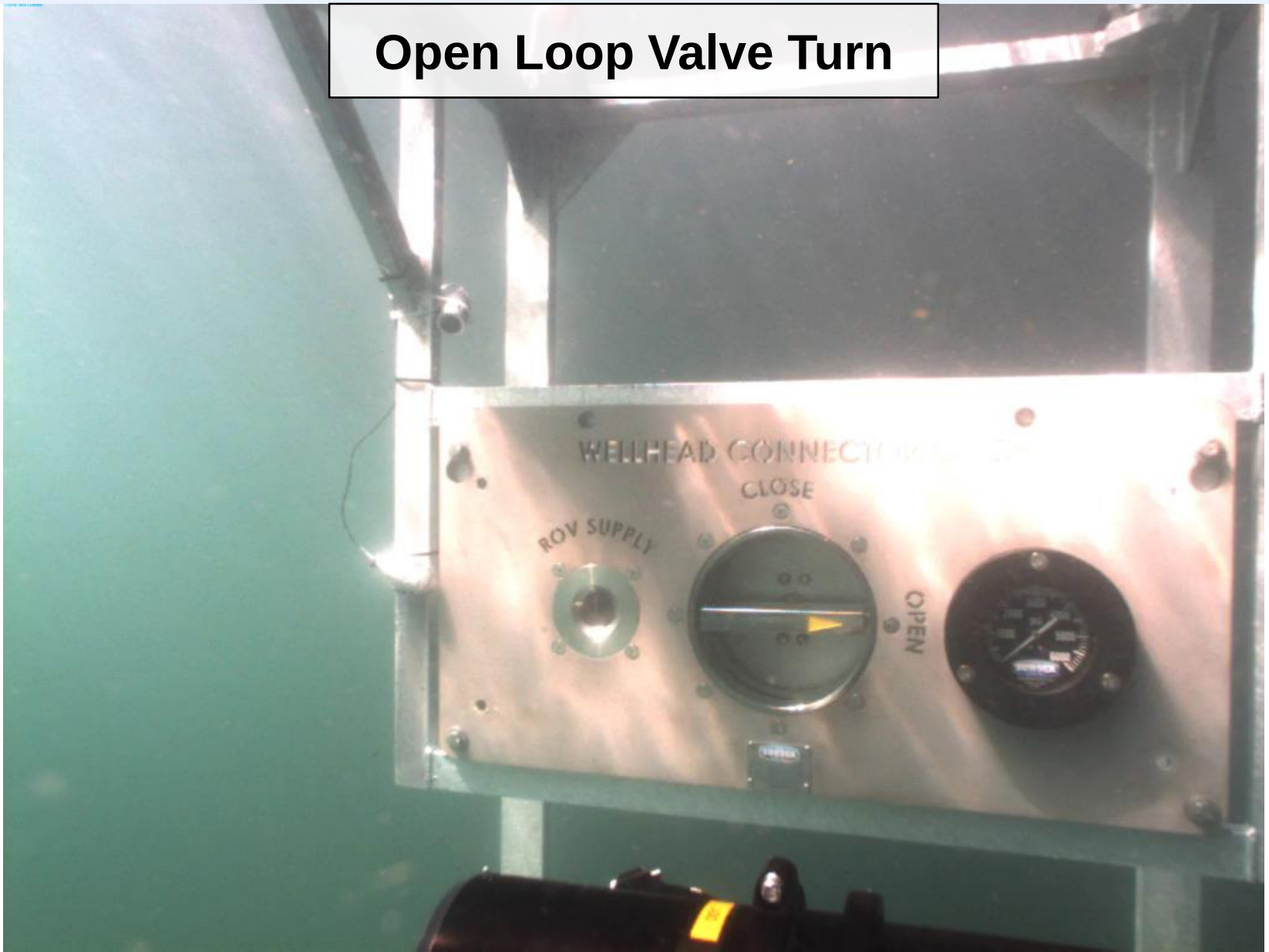


Paddle Valve Turn with Static End Effector

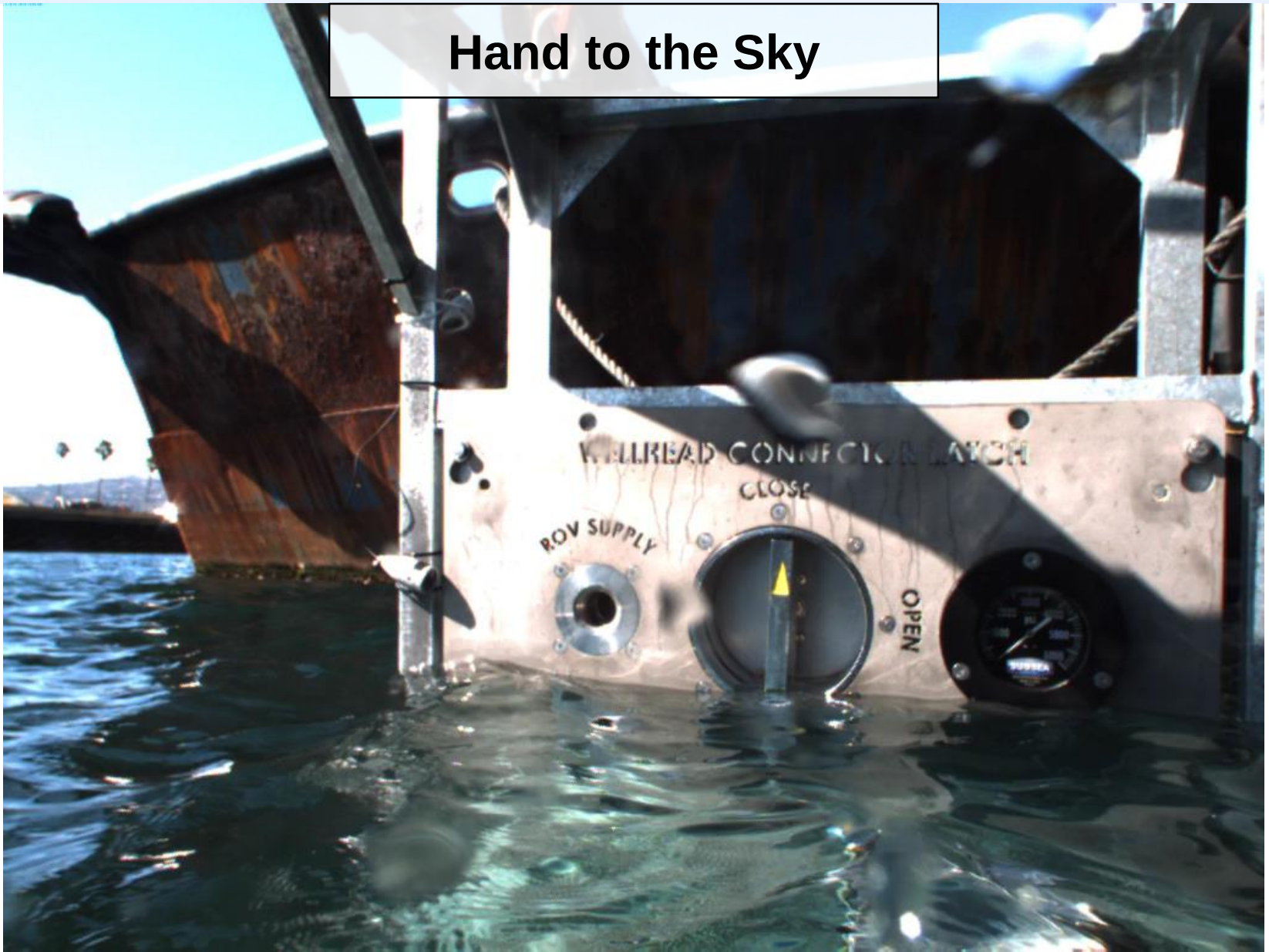
System Testing: Field



System Testing: Field



System Testing: Field



Future Work

Hardware

- 3 DoF End Effector with 6-axis F/T Sensor

Software

- CAD fitting in operator workflow
- Force in the loop insertion behavior

Demonstration

- Closed loop Hot Stab Insertion
- Closed loop Valve Turn

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